BAFFLE-POST STRUCTURES FOR FLOW AND BED-SEDIMENT CONTROL IN OPEN CHANNELS

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ABSTRACT

This paper presents theory and laboratory findings regarding the hydraulic performance of baffle-post structures used as a means for controlling flow in open channels. Such structures comprise one to two parallel rows of posts that extend slightly higher than the anticipated depth of flow, and offer a useful means for retarding flow in various channel situations where there is a need to reduce flow energy, possibly to reduce flow capacity to transport bed sediment and manage channel morphology. The laboratory findings were obtained using a tilting flume that produced data and observations on non-dimensional headloss and discharge coefficients and flow retardance (backwater flow profiles) associated with varying geometry of baffle-post structure. This information is of use in evaluating the extent to which a baffle-post structure, by retarding an approach flow, reduces the capacity of an approach flow to convey bed sediment and, thereby, promote channel bed aggradation.

INTRODUCTION

This study focuses on the hydraulic performance of baffle-post structures, illustrated in Figure 1. These structures act to slow or retard an approach flow, spread the flow across an approach channel, and sometimes disrupt large-scale turbulence structures in approach flows. They do so primarily by locally increasing flow resistance, reducing approach-flow velocities, and dissipating flow energy. The hydraulic performance of baffle-post structures, however, has received little attention. In particular, there appear to be no prior studies relating the geometric characteristics of baffle-post structures to hydraulic performance such as expressed using common indices, notably discharge and headloss coefficients associated with flow through baffle-post structures in open-channel flow.

By slowing or retarding an approach flow, and locally dissipating flow energy, baffle-post structures are used fairly often to help maintain the grade of a channel, and possible elevate and flatten the grade. This function is accomplished by the posts slowing and deepening the approach flow, letting flow and washload sediment pass, but causing a proportion of the approach bedload sediment transport to deposit on the channel bed upstream of the baffle-post structure.

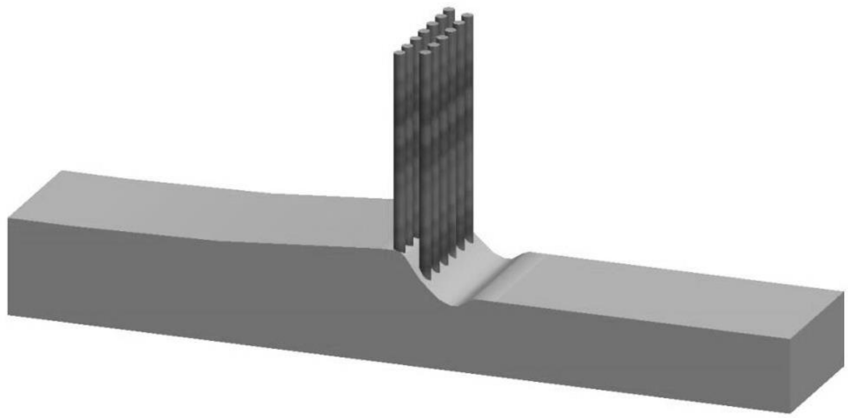

Figure 1: A Baffle post structure comprising a double row of posts spaced so as to suitably slow or retard an approach flow

The basic baffle-post structure consists of one to two rows of vertical posts. Depending on application, the post can be dowel timber, metal posts or rods, or tree trunks. When used in alluvial river channels, the posts typically are driven into the channel bed; in certain industrial uses, and laboratory flumes, the posts may be fixed to a base plate or cap block. The posts themselves usually are evenly spaced, with a second row staggered so that its posts align between those in the upstream row.

This paper briefly reviews the theory associated with the hydraulic performance of baffle-post structures, shows general trends for values of discharge coefficient and headloss related to them, and presents useful data for estimating the backwater extent (or M1 gradually varied flow profile) produced. This information is needed for evaluating the extent to which a baffle-post structure, by retarding an approach flow, reduces the capacity of an approach flow to convey bed sediment and, thereby, promote channel bed aggradation.

BACKGROUND THEORY

The essential function of a baffle-post structure is to retard an approach flow, slowing it, spreading it, and dissipating a portion of its energy. However, because flow at a baffle-post structure is non-uniform the analysis of structure hydraulic performance entails several simplifying approximations enabling baffle-post structure design to meet performance requirements within acceptable limits. The main requirement of interest for baffle-post structures in alluvial channels is the increase in water depth immediately upstream of the structure. A depth increase is associated with retarding of the approach flow so as to reduce the flow's capacity to transport bed sediment.

The hydraulic performance of a baffle-post structure can be evaluated in terms of the conservation of energy and continuity principles applied between the three flow cross sections indicated in Figure 2:

1. Between sections 0 and 1, where 0 indicates uniform approach flow well upstream of the structure, and 1 indicated a section immediately upstream of the structure; and,
2. Between sections 1 and 2, where 2 indicates the contracted section within the structure.

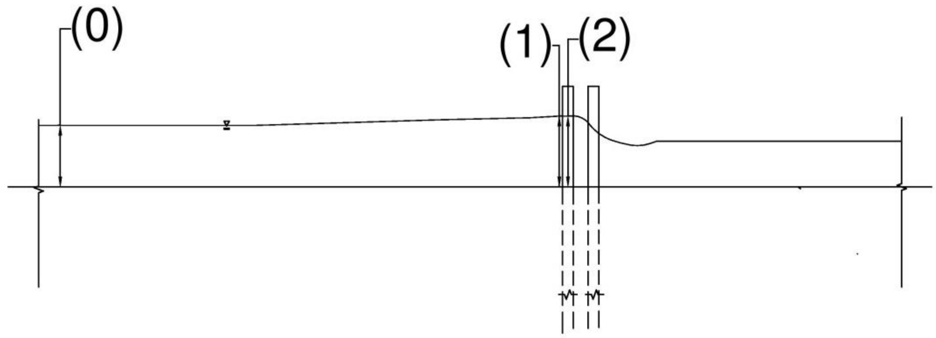

Figure 2: Three flow sections referenced for a double-row, baffle post structure

The specific energy diagram is a useful concept for explaining the hydraulic performance of a baffle-post structure. When the channel contracts, increasing the unit discharge, $q > q_0$, a set of curves exist, each with increasing value of critical depth, y_c, and E_{min}. Eventually, the contraction reaches critical width whereby E_{min} coincides with the initial specific energy, E_0. Associated with this critical flow depth is a critical width, b_c, defined as the maximum contraction the flow can pass through without becoming choked. In other words any constrictions narrower than b_c will produce an "overcritical" contraction so that there is not enough energy to maintain the given flow rate through the constriction. The critical width can be calculated as:

$$b_c = \left(\frac{3}{2}\right)^{3/2} \frac{Q}{\sqrt{gE_0^3}} \quad (1)$$

When the effective width of the flow constriction is less than b_c, the contraction acts as a "choke," as the available specific energy, E_0, is unable to pass the flow through the contraction. The flow backs up producing an M1 (backwater), gradually varied flow water surface profile, so as to elevate the magnitude of specific energy required to pass the flow through the contraction. The flow within the contraction stays critical, as the approach flow only backs up to the extent that generates the minimum energy needed to pass the given rate of flow through the contraction. The downstream flow may be supercritical or subcritical depending on the downstream conditions.

The additional energy becomes evident in the increased depth of flow at the contraction, and relatedly the energy increment, ΔE, needed to get the flow through the contraction. Figure 3 indicates the increase in specific energy and associated water depth upstream of the contraction. The increase in specific energy is dissipated as flow turbulence when the flow passes through the contraction and in a hydraulic jump formed immediately downstream of the contraction.

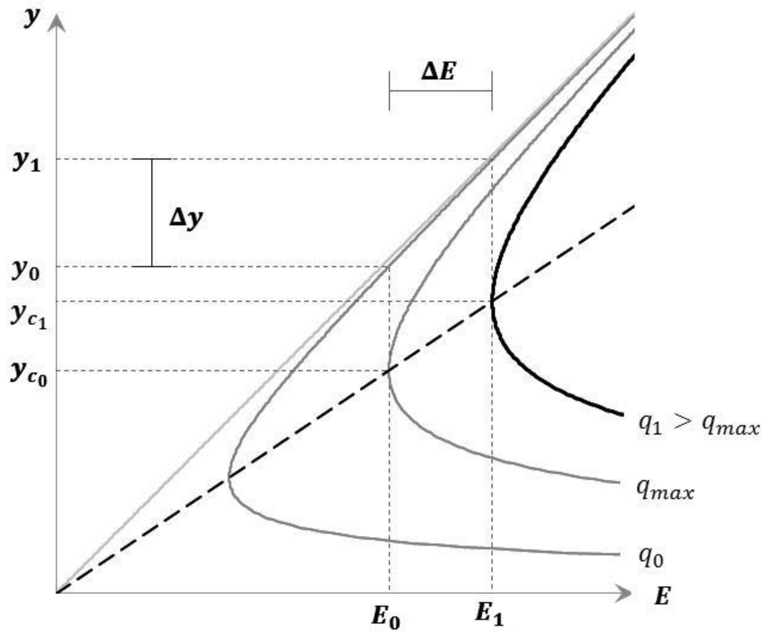

Figure 3: The increase in specific energy and upstream water level needed to pass the choked flow.

The additional energy, ΔE, needed to pass a give flow rate through a choked contraction can be evaluated in terms of the specific energy adjustments between sections 0 and 1: i.e.,

$$\Delta E = (y_1 - y_0) + \frac{q_0^2}{2gy_1^2} - \frac{q_0^2}{2gy_0^2} \tag{2}$$

Here, y_0 is the normal depth of flow for the uniform section well upstream of the structure, and y_1 is flow depth at section 1. Accounting for the headloss associated with flow resistance and the backwater curve, the headloss associated with the structure is:

$$\Delta E = h_{Lbaffle} = h_{L0} - h_{L0-1} = \left\{\left(\frac{fL}{8}\right)\left[\frac{(y_1/y_0)^3 - 1}{y_0(y_1/y_0)^3}\right]\right\}\left(\frac{u_0^2}{2g}\right) \tag{3}$$

It is common to express a local headloss, h_L, in terms of a headloss coefficient, C_L, and an average approach velocity, U_0, such as

$$h_L = C_L\left(\frac{u_0^2}{2g}\right) \tag{4}$$

Here

$$C_L = \frac{(y_1 - y_0) + \frac{q_0^2}{2gy_1^2} - \frac{q_0^2}{2gy_0^2}}{\left\{\left(\frac{fL}{8}\right)\left[\frac{(y_1/y_0)^3 - 1}{y_0(y_1/y_0)^3}\right]\right\}\left(\frac{u_0^2}{2g}\right)} = \frac{1}{\left\{\left(\frac{fL}{8}\right)\left[\frac{(y_1/y_0)^3 - 1}{y_0(y_1/y_0)^3}\right]\right\}} C_L' \tag{5}$$

The term is a cumbersome expression relating to flow resistance in the approach to the structure, and shows that a unique value headloss coefficient, C_L, does not exist for a baffle-post structure.

DIMENSIONAL ANALYSIS

To work around the complications related to the non-uniform nature of the flow at a baffle-bar structure, it is useful to resort to dimensional analysis, which also offers a framework for assessing how approach-flow conditions and baffle-bar structure influence the hydraulic performance of baffle-bar structures. The dominant variables influencing flow and energy dissipation through a baffle-bar structure can be assembled and stated in the following functional manner:

$$f(N, D, s, l, Y_0, q_0, B, g, \nu) = 0 \tag{7}$$

Where N is the number of baffle bar rows, D is the baffle bar diameter, s is the lateral spacing, from center to center, of the baffle bars, l is the streamwise spacing, from center to center, of the baffle bars, y_0 is the flow depth at section 0, q_0 is the unit discharge at section 0, B is the width of the channel,g is the unit gravity constant, and ν is the kinematic viscosity of water.

Eq. (7) assumes fully turbulent flow with neglible surface tension effects. Applying the general principles of dimensional analysis, dimensionless relationships can be formed for C_L and C_D. Additionally, a dependent parameter of practical design interest is the depth increase parameter, y_1/y_0, as this parameter is usually required in order to select the geometric layout and dimensions of a baffle-bar structure. Therefore, an important functional relationship for design is,

$$\frac{y_1}{y_0} = f_D\left(N, \frac{s}{D}, \frac{l}{D}, \frac{y_0}{D}, Fr_0\right) \tag{8}$$

The laboratory experiments conducted for this study explore the relationship between the parameters in this equation.

LABORATORY EXPERIMENT

Experiments were conducted to determine the influences of baffle-post geometry (number of rows, post spacing and post diameters) on the hydraulic performance of baffle-post structures. The hydraulic parameters of interest are C_L' and y_1/y_0. They involved a re-circulating open channel flume that was 9.70m long, 0.20m wide and 0.36m deep at Colorado State University's (CSU) Hydraulic Laboratory.

The baffle-post models comprised cylindrical wooden dowels attached to a piece of wood secured to the top of the flume. The structure geometry was developed assuming 0.30m baffle post diameters for the prototype. Using a morphologic relationship, the posts were sized using a width ratio of 18 (prototype/model), which is based on a relaxed scaling approach used in the Mount Saint Helens GBS physical model. A 19.2 width ratio was adopted for practical purposes, as dowels are only available in standard sizes.

For single-row structures, post diameter and streamwise spacing were fixed. Only the relative lateral spacing $\frac{s}{D}$, was varied from 1.5 to 6.4. Experiments of single-row structures included two Froude numbers $(Fr_0 = 0.15, 0.45)$ and four relative depths. All three parameters (lateral spacing, streamwise spacing, and post diameter) were altered for the double row structure. Three different relative depths were experimented at a range of Froude numbers ranging from 0.10 to 0.58.

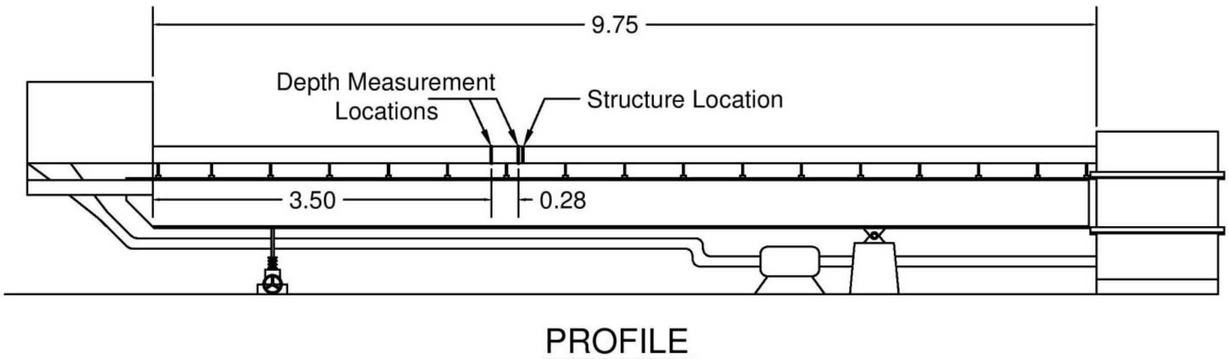

Figure 4: Profile view of the flume showing measurement locations for flow depths and velocities. Dimensions are in meters.

LABORATORY OBSERVATIONS AND DATA

The full set of observations and data are reported by Ubing (2015). This paper briefly describes the flow field at baffle-post structures, outlines the general trends obtained for the headloss coefficient, C_L', and a selection of data for the normalized flow depth increase y_1/y_0.

Flow Field at Baffle-Post Structures. When approaching the structure the flow transitions from uniform flow conditions into gradually varied flow conditions, where the depth is increasing gradually–until it reaches the maximum depth, directly upstream of the structure. Figure 5 illustrates the flow field. The depth increases to increase the specific energy upstream of the structure to pass the given flow discharge though the structure. At this point within the control volume, the velocity within the channel is the lowest. The flow accelerates through the structure, due to the width constriction. Directly downstream of the structure, the flow continues to accelerate, resulting in a rapid decrease in flow depth, eventually reaching the point of minimum flow depth, or maximum flow velocity. This location varies in its magnitude as well as its streamwise distance from the structure. Finally, the flow will gradually or rapidly increase, depending on initial flow conditions and the structure geometry. If choked flow conditions occurred, and the downstream depth become critical, it is likely that a hydraulic jump will occur within this section.

Figure 5: Side view of the flow field at a double-post baffle-post structure

Headloss Coefficient. The general impacts of structure geometry on the uniform flow headloss coefficient, C_L', are shown in Figure 7. Overall, C_L' decreased as the Froude number increased, because of the relationship between $C_L'$and Fr_0 indicated in Eq. (5). Lateral spacing, or *s/D*, has the greatest impact on C_L', causing the headloss coefficient to increases as lateral spacing decreases. As streamwise spacing increased, the headloss coefficient also decreased, but to a lesser extent. Finally, an increase in post diameter resulted in a slight increase in headloss coefficient. The discharge coefficient remained relatively constant over the experimented range of Froude numbers.

Closer spacing results in higher roughness through the baffles due to an increase in turbulence. When the flow openings are smaller, the flow vortices developed due to the baffle bars are closer together and more likely to interfere with each other, which results in a more turbulent flow and higher internal energy dissipation. The primary driver of an increase in energy dissipation is a direct result of higher blockage ratio, as shown in Figure 6. The additional baffle posts obstruct a larger flow area, producing higher resistance to flow, thus dissipating more flow energy.

At lower Froude numbers, the headloss coefficient also varied with relative depth, especially at smaller relative lateral spacing. Physically, the decrease in headloss coefficient with an increasing relative depth can be explained by the magnitude of the various vortices. At small relative depths, the downflow and horseshoe vortex will collide with the channel bottom, resulting in an increase in turbulence, which will further dissipate the energy within the flow. However, as the depth increases, the horseshoe vortex moves up the water column, no longer interacting with the channel bottom.

The relative depth appeared to have minimal impacts at the larger Froude number, due to the direct relationship between relative depth and energy dissipation. The relative change in water surface elevation produced by a structure increases as y_0/D increases. Therefore, both the velocity head, $\frac{u_0^2}{2g}$, and the energy dissipation, ΔE, increase, resulting in a less variable headloss coefficient. Furthermore, at a higher Froude number both the horseshoe and roller vortices are much stronger and larger and possibly interacting at all three relative depths. Therefore, the additional energy dissipation as a result of the colliding flow paths is likely observed at all three relative depths, resulting in negligible differences in the headloss coefficient through the structure.

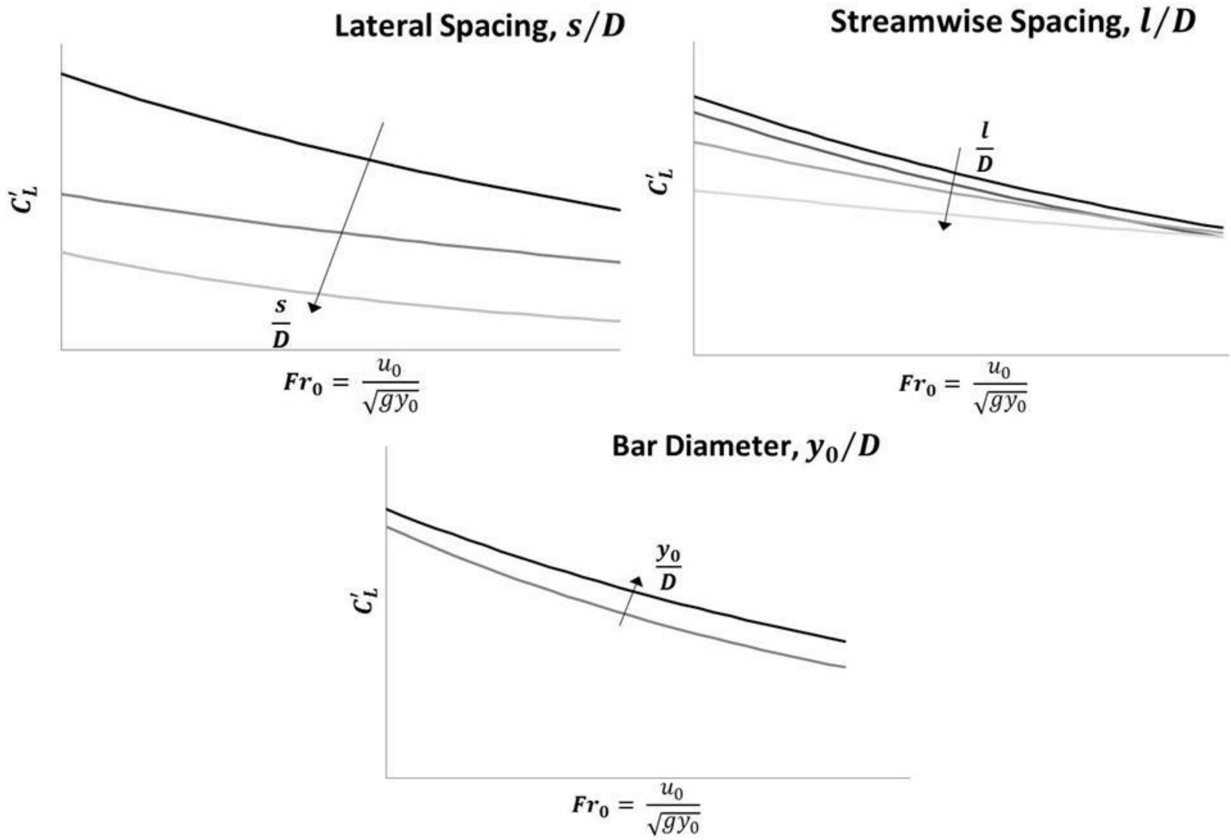

Figure 6: Schematic presentation of the general trends obtained for headloss coefficient C ʹL
(Data in Ubing 2015)

Backwater (Flow Retardance) Effect, y_1/y_0. The trends shown in Figure 7 illustrate how post spacing, *s/D*, and Froude number of approach flow, Fr_0, influence the values of the flow depth parameter y_1/y_0. Thus, the baffle-post structures created the backwater flow which acts to slow or retard an approach flow. The structures used to obtain the data for this figure entailed posts set at a streamwise spacing of *l/D* = 2. The value of y_0 for an approach flow (or flow prior to installation of a piffle-post structure) can be calculated, using say the Manning's equation, and then together with the value of Froude number, Fr_0, for the approach flow, the flow depth, y_1, at the baffle-post structure estimated using Figure 7. From the flow depth at the structure, y_1, the upstream dimensions of the backwater flow profile (M1 flow profile) can be calculated. In due course this backwater profile can be interpreted for its effect on the capacity of the approach flow to convey bed sediment.

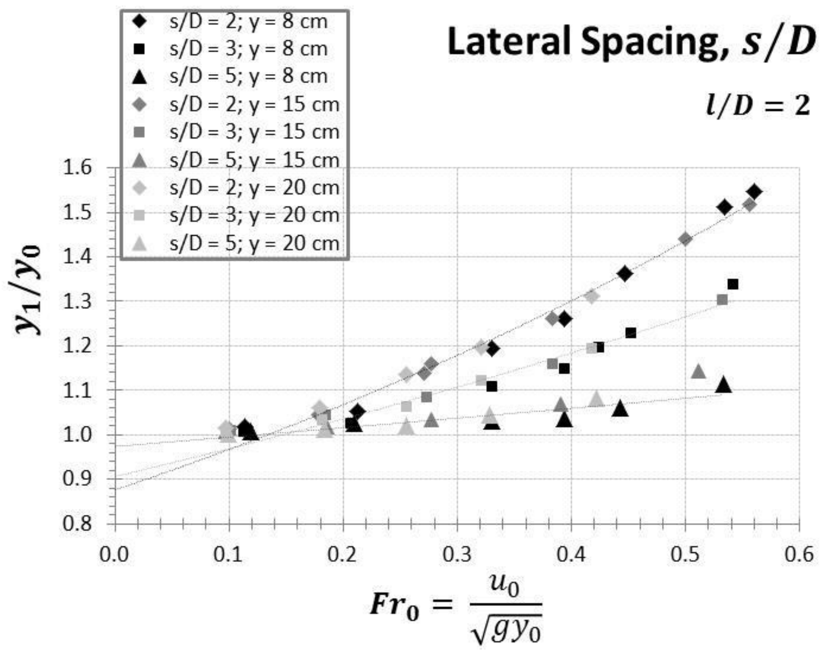

Figure 7: The variation of flow depth parameter y_1/y_0 for a double-row baffle-post structure with rows spaced at l/D = 2. The additional parameter in this figure is y_0/D, which exerts only a very small effect for the range of values investigated.

An important consideration in the use of baffle-post structures is the need for rock armoring to be placed around the base of the posts and the immediate downstream region where the flow passes through a hydraulic jump. The details related to tis consideration are presently under investigation at CSU.

CONCLUSIONS

This paper presents early observations regarding the impacts of geometric characteristics on the hydraulic performance of a baffle post structure. The observations, from laboratory experiments show that lateral spacing had the largest impact on the headloss and discharge coefficients; whereas, the post diameter and streamwise spacing appear to have near negligible impacts on the headloss and discharge coefficients. Relative flow depth impacted the headloss coefficient only at lower Froude numbers due to the magnitude of various flow vortices. At larger Froude numbers, the vortices are larger and stronger; therefore, colliding at three relative depths. In general, the headloss coefficient decreased as the Froude number increased. However, the discharge coefficient remained relatively constant within the range of tested Froude numbers.

Choked flow conditions only occurred at higher Froude numbers, with smaller relative lateral spacing. At smaller Froude numbers, the discharge through the channel was not large enough to induce choked flow conditions through the effective width of the structure. As the discharge increased and the critical width of the flow increased, the contraction became large enough to “choke” the flow.

Further work is needed to investigate other relevant aspects of the structure geometry such as baffle shapes, staggered rows, and random configurations. Also, further work is needed to determine the bed-protection needs to inhibit local scour at a baffle-post structure. Investigation to the impact of the roughness of the baffle posts should be made to determine if the tree post will influence the energy dissipation through the structure. Additional experiments studying the impacts of variable diameter within a single structure is recommended as available materials may not provide uniform baffle posts. Finally, tests were conducted with initial Froude numbers varying between 0.10 and 0.58, all of which are within the region of subcritical flow. Supercritical flow does not occur often over large spatial extents in nature. However, the author recommends testing the structure in supercritical flow conditions to determine if the headloss coefficient curve deviates when $Fr > 1.0$.

The limitations inherent in determining general trends for discharge and headloss coefficients indicate that further investigation will benefit from an approach by means of dimensional analysis identifying the functional relationships between these parameters and approach-flow and structure geometry. Also of practical importance is the relationship between approach flow depth and flow depth at the structure, y_1/y_0; this parameter is significant in determining the backwater effects produced by a baffle-post structure.

ACKNOWLEDGEMENTS

This study was conducted as part of a background effort for a larger project aimed at designing and testing a series of grade-building structures for possible use in the Toutle River in Washington. The information presented here has yet to be further developed for potential use in this larger project, which is funded by the Portland District of the U.S. Army Corps of Engineers.

REFERENCES

Ubing, C. (2015). “The Hydraulics of Baffle-Post Structures.” MS thesis, Colorado State University, Ft.Collins, CO